# Modeling nuclear and electronic recoils in noble elements with NEST

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# **NEST**:

# The **N**oble **E**lement **S**imulation **T**echnique

NEST is a(n):

- Detector-independent simulation framework
- Comprehensive physical model of low energy interactions in liquid xenon
- External package compatible with Geant4, for easy integration into simulations
- Stand-alone code for fast calculations of yields and rates in simplified situations (available soon)

NEST is free and publicly available:

**http://www.albany.edu/physics/NEST.shtml**

**http://nest.physics.ucdavis.edu**

# The NEST collaboration

**University at Albany, SUNY**

- Prof. Matthew Szydagis
- Dr. Jeremy Mock
- Steven Young
- Sean Fallon
- Zakia Sultana
- Jack Genovesi
- Steven Cifarelli

**University of California, Davis**

- Prof. Mani Tripathi
- Prof. Emilija Pantic
- Dr. Aaron Manalaysay
- Dr. Scott Stephenson

**Lawrence Livermore National Laboratory**

- Dr. Kareem Kazkaz
- Brian Lenardo

**University of California, San Diego**

- Prof. Kaixuan Ni
- Fei Gao*

**University of Tennessee**

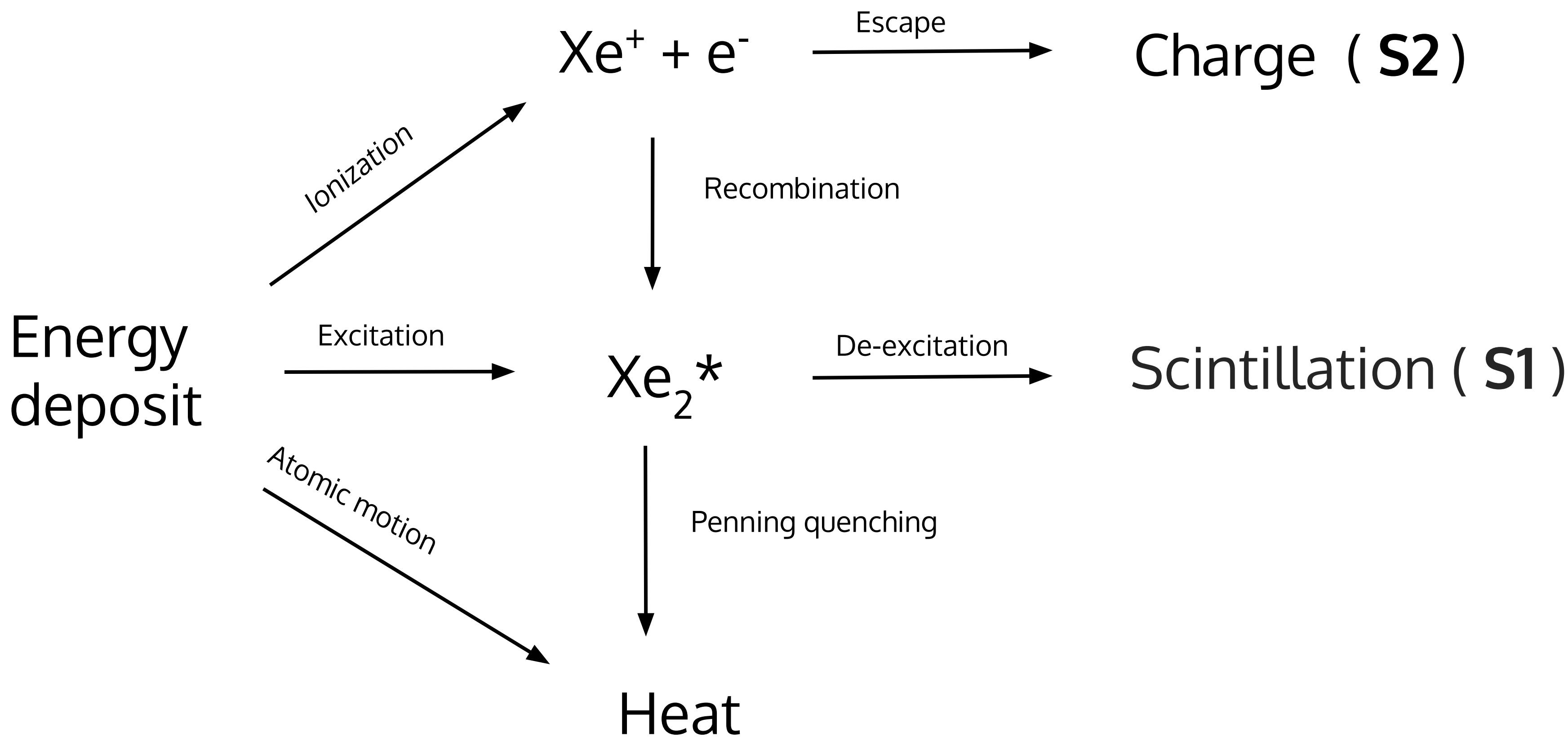
- Prof. Sergei Ovchinnikov

**SLAC National Accelerator Laboratory**

- Prof. Tom Shutt
- Prof. Dan Akerib

*Affiliated with Shanghai Jiao Tong University

# Signal production in liquid xenon




NEST models this process start-to-finish for both ER and NR

# NEST algorithm

$$N_q = \frac{E_{\text{dep}}}{W}$$

NR

$$N_q = N_q\, L$$

ER

$$N_{\text{ion}} = \frac{N_q}{1 + (N_{ex}/N_{ion})}$$

$$N_{\text{ex}} = N_q - N_{\text{ion}}$$

$$n_e = (1-r) N_{\text{ion}}$$

$$n_\gamma = (N_q - n_e)\, \frac{1}{1 + \alpha\, \epsilon^{\beta}}$$

Thomas-Imel recombination model

$$r = 1 - \frac{\ln(1 + N_i\, \varsigma)}{N_i\, \varsigma}$$

Lindhard suppression of NR signal

$$L = \frac{k\, g}{1 + k\, g}$$

# NEST algorithm

Thomas-Imel recombination model

$$r = 1 - \frac{\ln(1 + N_i\,\varsigma)}{N_i\,\varsigma}$$

$N_q =$ ...

$N_q =$ ...

Lindhard qu...

$L$ ...

NEST predicts absolute number of electrons AND number of photons.

- Conserves energy
- Assumes anti-correlation

Energy scale uses combined information to improve resolution

$$E_{ER} = (n_\gamma + n_e)\,W$$

$$E_{NR} = \frac{(n_\gamma + n_e)\,W}{L}$$

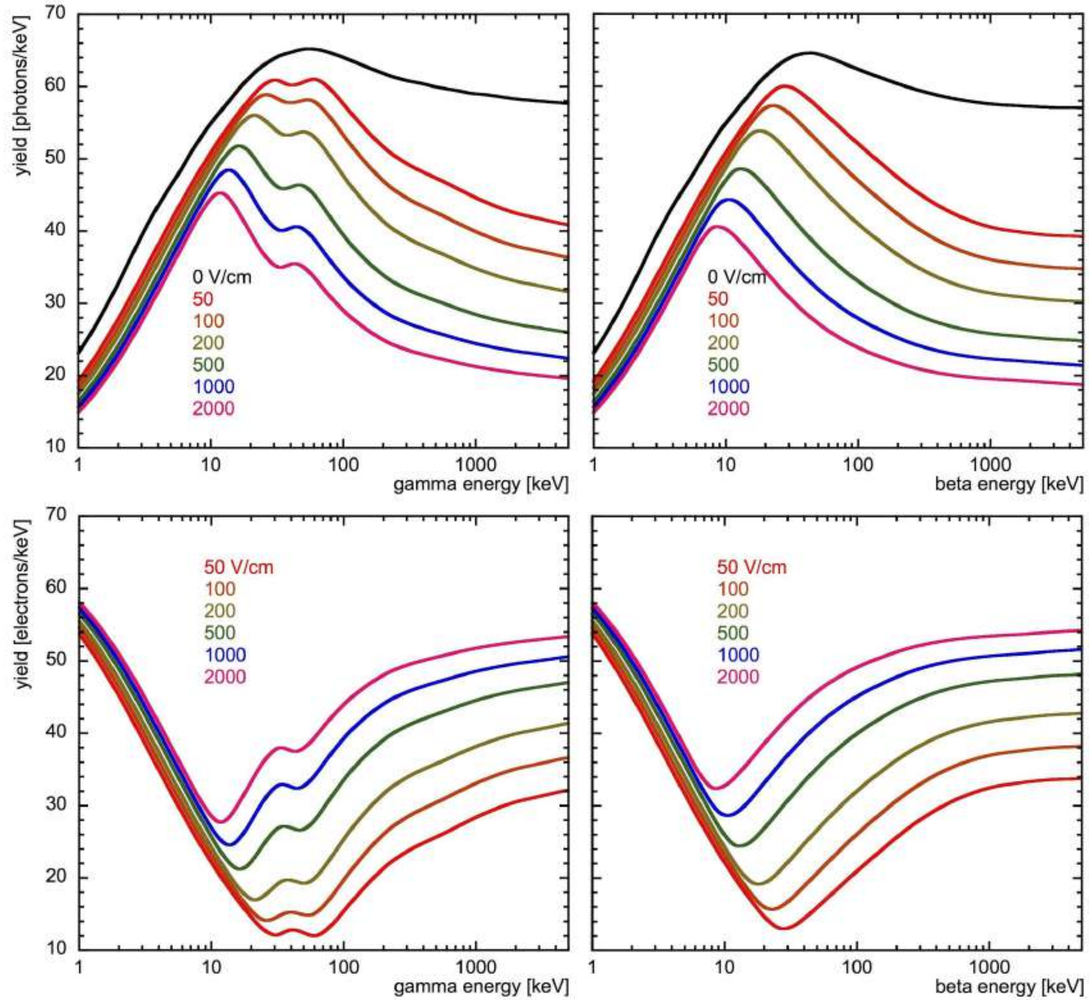
$$n_e = (1 - r)N_{\rm ion}$$

$$n_\gamma = (N_q - n_e)\,\frac{1}{1 + \alpha\,\epsilon^\beta}$$

# The electron recoil (ER) model

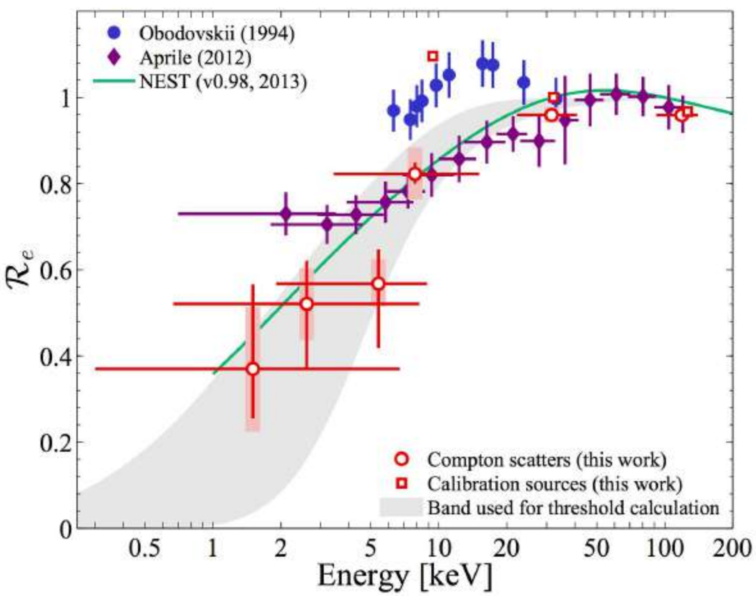
Light yield

Charge yield

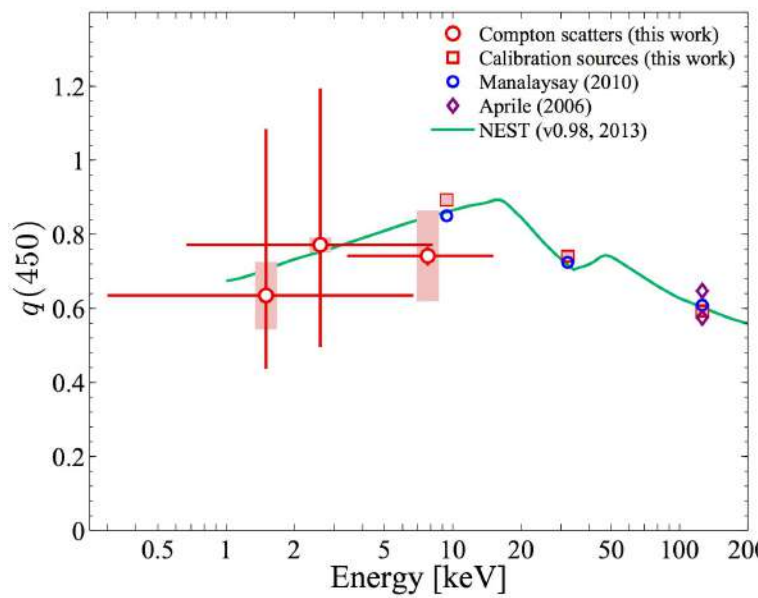


# The electron recoil (ER) model

No applied electric field




Fractional yield at 450 V/cm




Baudis et al., Phys. Rev. D 87 (2013) 115015

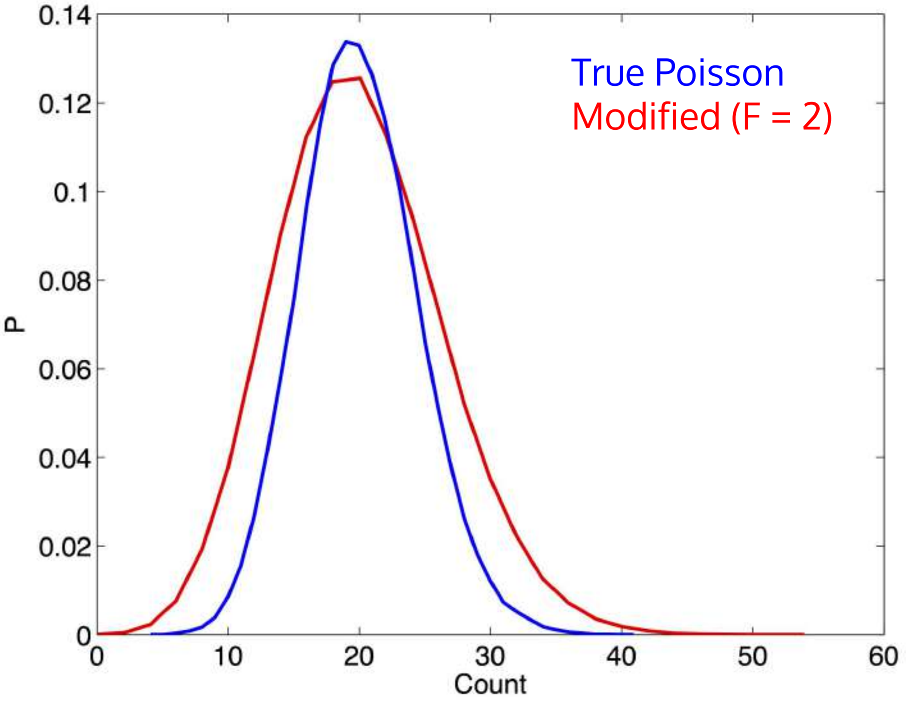
# Fluctuations in yields

Critical for modeling discrimination and resolution.

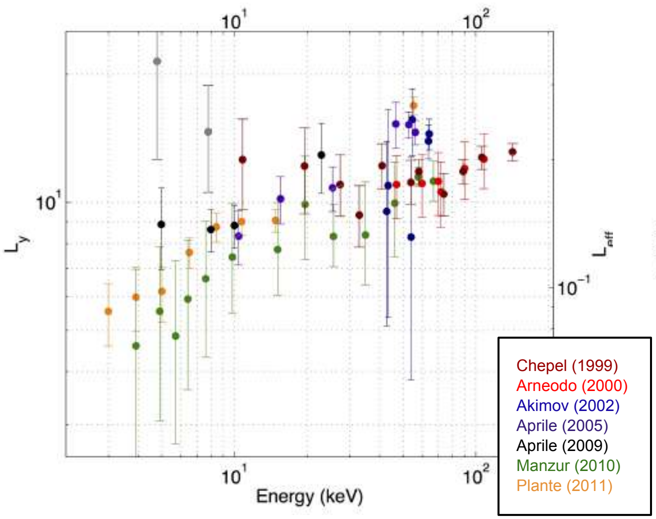
We use a modified Poisson:

x = floor( F * ( PoissonRnd( mu / F ) + UniformRnd )

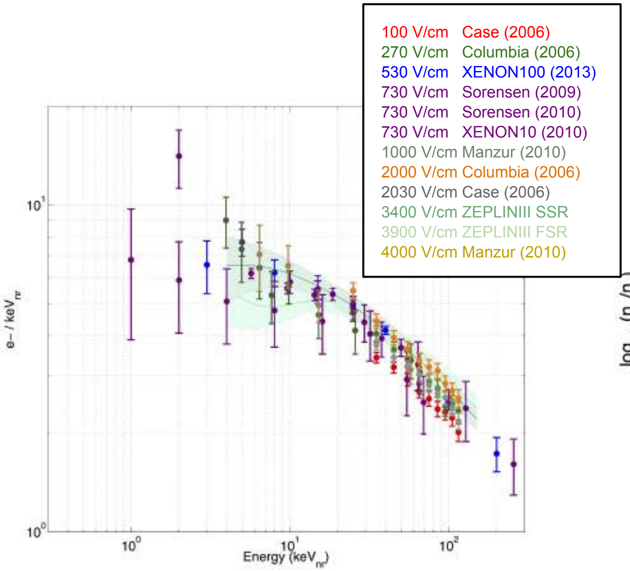
where F is an effective Fano factor that changes the generation of quanta



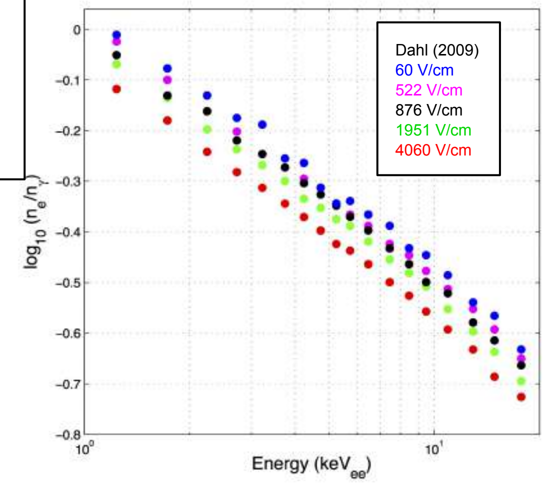
# Global fit to the world's data (NR)




$L_{eff}$ - scintillation yield




$Q_y$ - ionization yield




Electron / photon ratio

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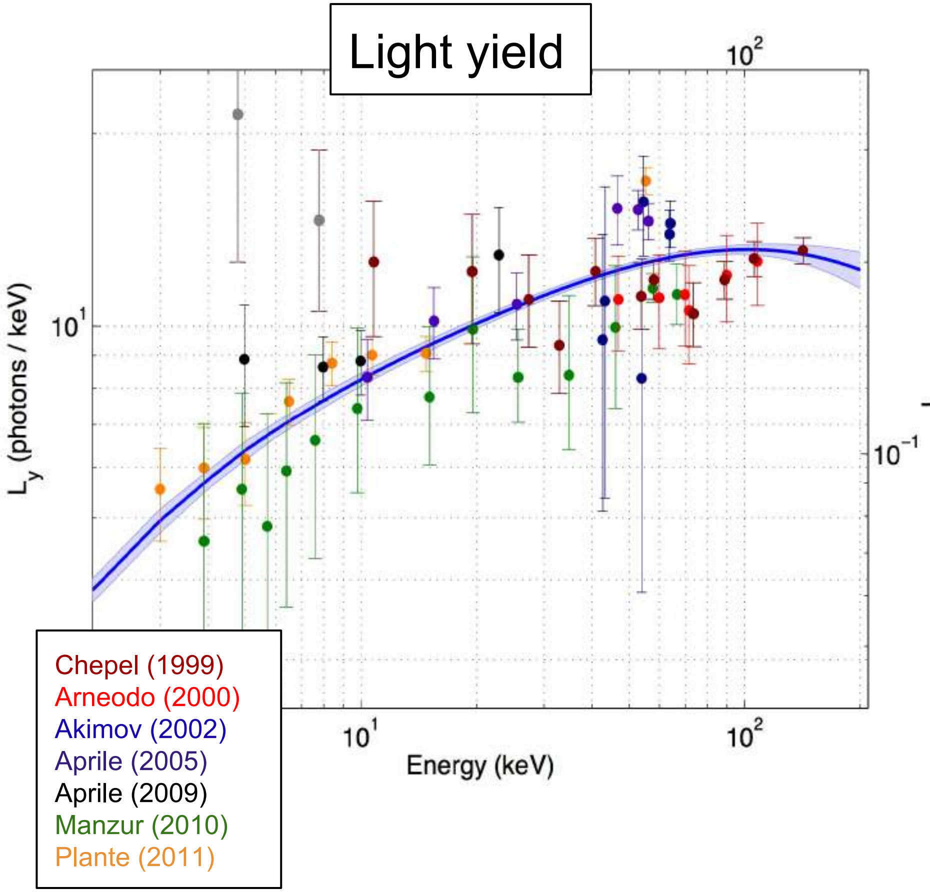
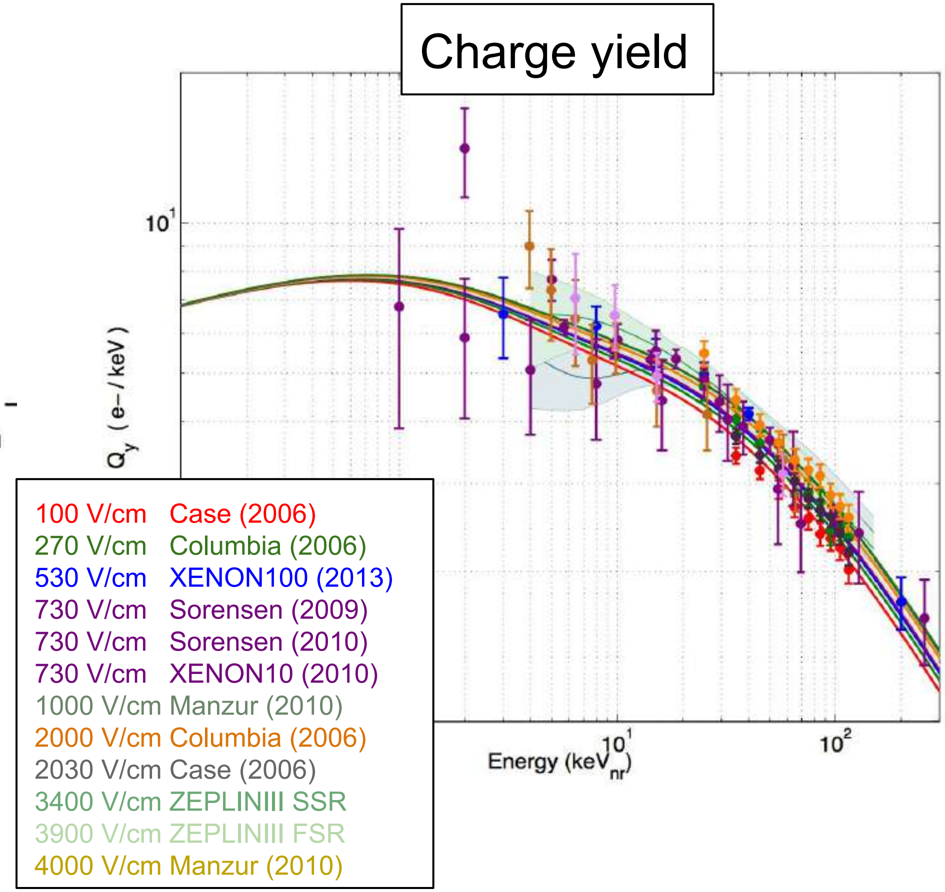
To fit to all of these data, we construct a global likelihood function and optimize.

$$\mathcal{L} = \prod \frac{1}{\sqrt{2\pi}\,\sigma_{exp}} \exp\left(\frac{-(x_{exp}-\mu)^2}{2\,\sigma_{exp}^2}\right) \qquad \mu \in \left\{ \mathcal{L}_{eff},\, \mathcal{Q}_y,\, \frac{N_e}{N_{ph}} \right\}$$

# Global fit to the world's data (NR)

Nuclear recoil model constrained with a global analysis of available data, see arXiv:1412.4417, submitted to TNS



# Advantages of the global analysis

- Constrains light and charge simultaneously; one affects the other
    - Stronger constraints than looking at either individually
- Includes all measurements in the literature in an unbiased way
- Can predict / incorporate new data as it becomes available

The resulting model allows us to interpret and simulate experimental data in a way that **reflects the cumulative body of research** on liquid xenon response.

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- Includes all measurements in the literature in an unbiased way
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See many of the other talks in this session!

- Koichi Ichimura ( 2:00 pm )
- James Verbus ( 2:20 pm )
- Qing Lin ( 3:00 pm )
- Dan McKinsey ( 4:50 pm )
- Elizabeth Boulton ( 5:30 pm )
- Dongqing Huang ( 5:50 pm )
- Attila Dobi ( 6:10 pm )

The resulting model allows us
way that **reflects the cumulat**

# Current / future work

# First-principles recoil modeling

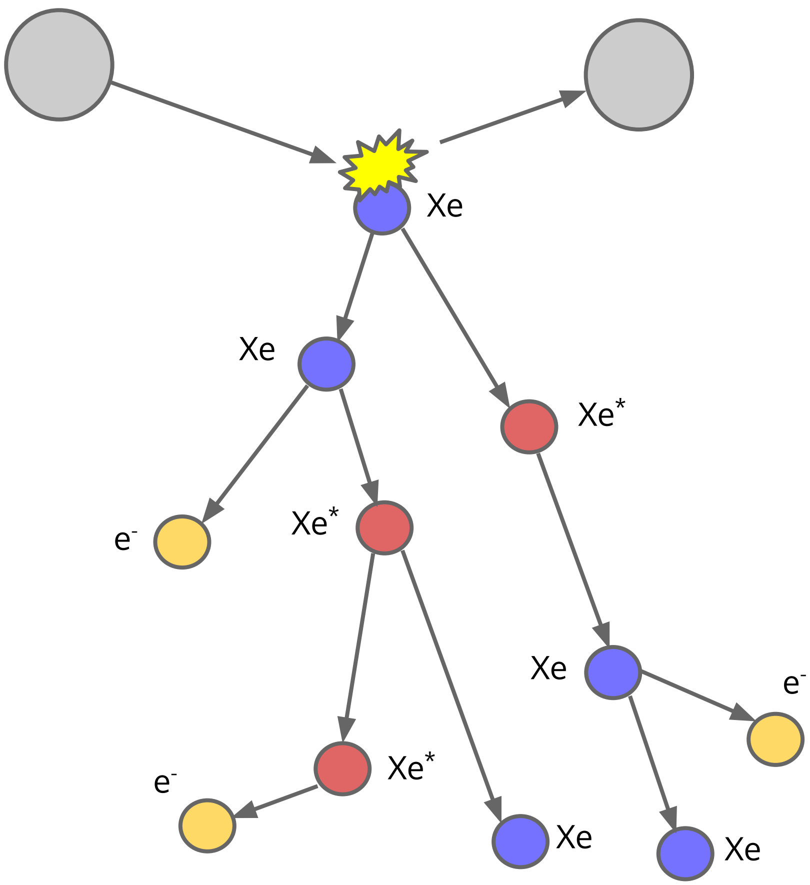
Cascades modeled using MC in LAr:

Foxe, M. et al., NIM A, Volume 771, p. 88-92.

Need to know several cross-sections:

- Xe-Xe ionization
- Xe-Xe excitation
- Xe-Xe elastic scattering
- $Xe^*$-Xe interactions
- $Xe^+$-Xe interactions

No measurements; calculations being done at University of Tennessee



# Systematics in the literature

## Energy scale / uncertainties

- Energy scales are determined differently in different papers
- Uncertainties in energy are inconsistently reported

## Electron extraction efficiency from liquid

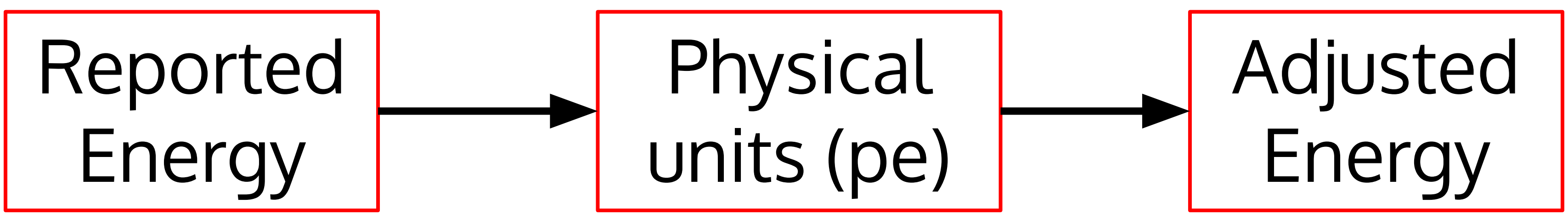
- Results in systematic up/down shift in measured charge yield

# Energy scale

Measurements use different energy scales:

- Absolute (known energy scatters)
- S1-only

To fix this, adjust energy scales:




- For cases with S1-only energy scales

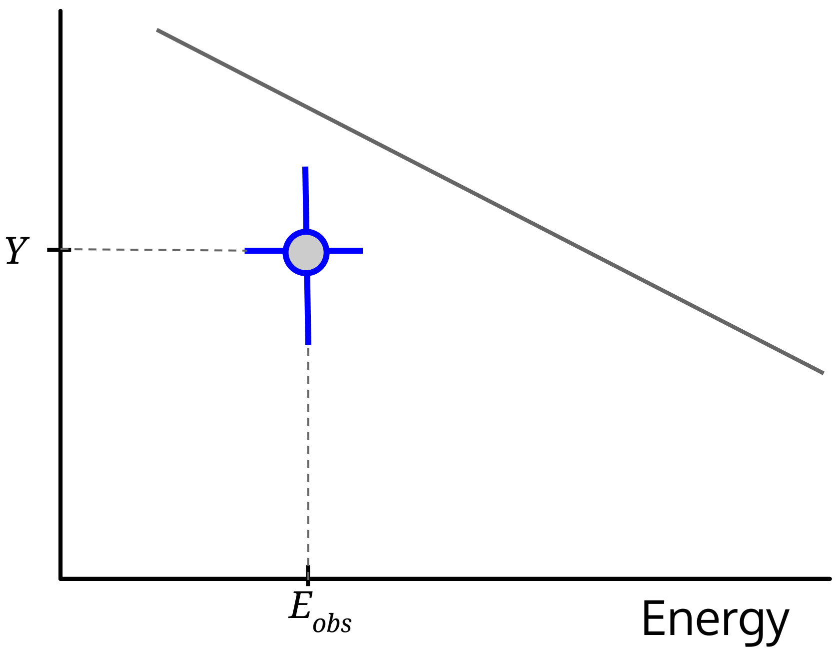
- Using collection eff. or $^{57}$Co calibration

- Also estimate energy uncertainties

# Energy errors

Uncertainties in energy can be incorporated using a **joint likelihood:**

$$\mathcal{L}(Y, E_{obs}) = \int \mathcal{L}(\,Y \,|\, E; \sigma_Y; \theta)\; \mathcal{L}(E \,|\, E_{obs}; \sigma_E)\; \mathrm{d}E$$

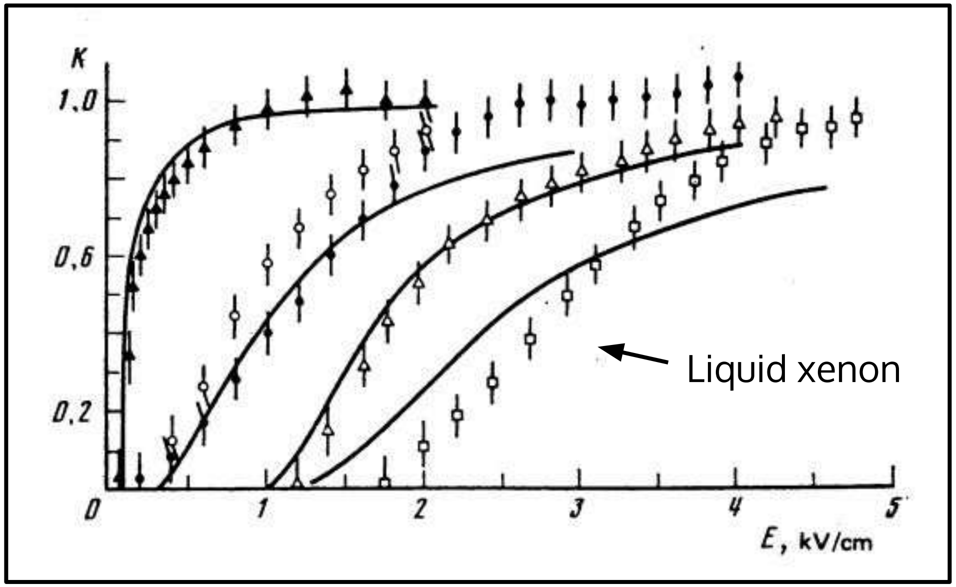



Likelihood of Y given:
- *E*
- Y errors
- NEST parameters ($\theta$)

Likelihood of *E* given:
- Observed energy
- Error in $E_{obs}$

Adapted from Eq. 4.1 of
C. Hsaio, *Journal of Econometrics* **41** (1989)

# Extraction efficiency

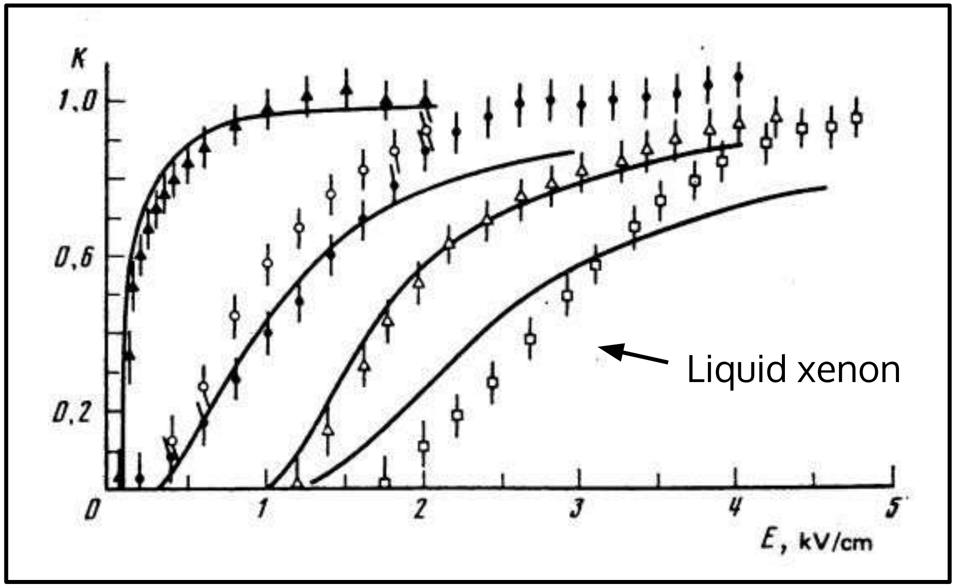



E. M. Gushchin et al.
Sov. Phys. JETP **55** (5), May 1982

Electron extraction changes with electric field

- Systematic shift in charge yield measurements
- Some measurements assume 100% (no uncertainty)
- Some measurements rely on old data

# Extraction efficiency

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This is even more important for larger detectors, where fields are limited by electrostatic breakdown

# Conclusions

- NEST is a tool by and for the liquid xenon community for modeling detector response
- Global analysis allows the inclusion of all available data in an unbiased way
  - For NR data, results are currently public ( arXiv: 1412.4417 )
  - For ER data, this effort is underway
- New efforts push to understand systematics in different measurements
- A plethora of new data (much of it presented here at LIDINE!) can be incorporated to make NEST as robust as possible

# Backup

# Preliminary results

Allow extraction efficiency (EE) to float in global fit to NR data

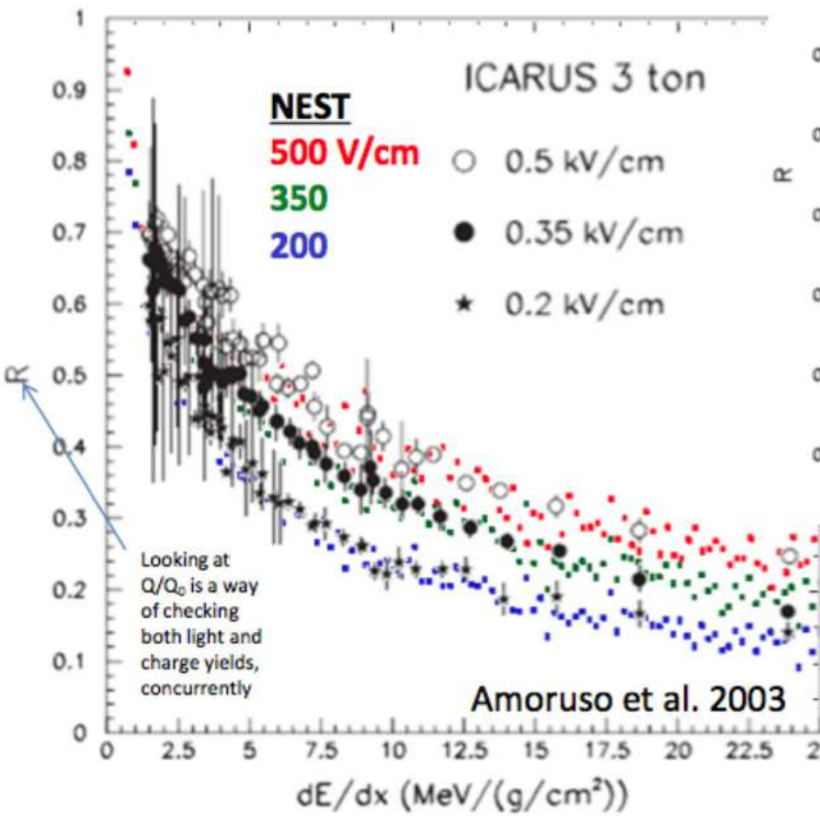
- Constrained assuming a gaussian truncated at EE = 1.0

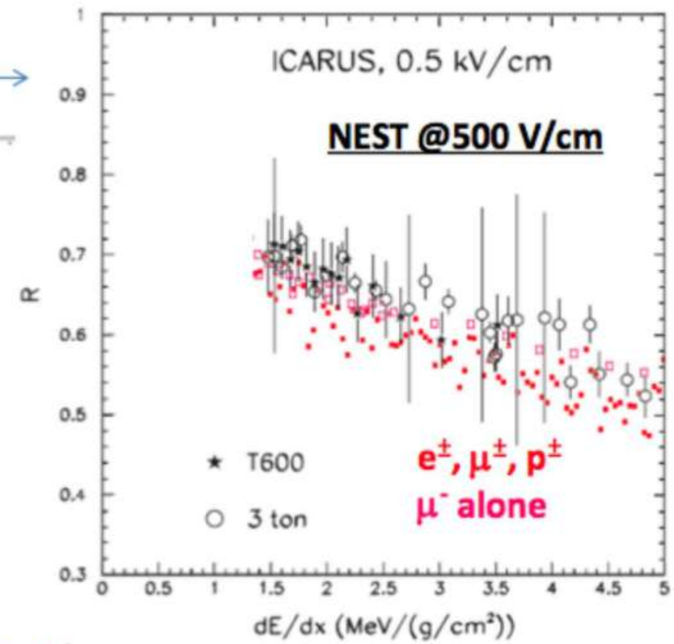
Shift required of charge yield ( $\mathbf{Q_y}$ ) data is very small.

| Publication | Gush. EE | Best-fit EE | % shift in $\mathbf{Q_y}$ |
|---|---|---|---|
| Aprile 2006 (Columbia) | 0.979 | 0.975 | 2.5 % |
| Aprile 2006 (Case) | 0.979 | 0.9825 | 1.75 % |
| XENON100 | 0.999 | 0.997 | 0.3 % |
| XENON10 | 0.999 | 0.999 | 0.1 % |
| Dahl (2009) | 0.979 | 0.999 | 0.1 % |

# Liquid Argon

Particle type does matter!




*dE/dx* is more important than energy, and the tracking of the stochastic variation in the secondary track history, step by step, is also crucial to get right